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Designing for Sustainability

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Designing for Sustainability

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Summary

In addition to impacting non-renewable energy supplies, buildings world wide contribute to climate change by being responsible for the release of carbon dioxide, either directly through combustion of carbon-based fuels or indirectly through electricity consumption from carbon fuels. As engineers and architects, we have an obligation to design for sustainability. This paper addresses each step in the building design process – from inception to occupancy. Recommendations and examples of how we can meet our obligations of sustainability are given using two examples of actual buildings that have low energy use and minimal impact on the environment. In addition, these buildings have life cycle costs comparable to conventional buildings and provide comfortable, healthy, and productive indoor environments.

Introduction

Buildings, some of society's most permanent and long-lived products, significantly impact global resources. Their continually increasing impact will make insurance of a sustained future even more challenging. Currently, buildings account for approximately 35% of the total energy used in the United States, including 65% of the nation's electrical consumption (1). Of the total energy consumed by buildings, 48% (the largest single component) is used for comfort cooling and refrigeration (2).

Buildings contribute to climate change by releasing carbon dioxide into the atmosphere. Carbon dioxide and other pollutants are the result of buildings consuming electricity, produced from burning non-renewable fossil fuels, or burning carbon-based fossil fuels within the building. In 1998, U.S. buildings alone were responsible for the release of approximately 114 million metric tons of CO_2 (3). This is in addition to the estimated 67,000 metric tons of SO_x and 35,000 metric tons of NO_x that they also release into the atmosphere. These numbers do not reflect the other impacts of producing electricity from fossil fuels including heat added to cooling water, environmental damage from strip coal mining, and aesthetic impacts of power plants and the related electrical distribution system.

There has long been a demand to improve climate control in buildings. Buildings were once designed to maintain comfort in the climate where they were located. Heating was relatively easy – put a fireplace in every room that was to be heated. Cooling was achieved with good building architecture. Windows were designed for cross-ventilation and stack effect ventilation. Windows were also shaded to prevent unwanted summer solar gains. High ceilings and fans helped maintain comfort. The introduction of boilers helped meet the heating requirements; however, limited cooling was still accomplished with the design of the building. The invention of central cooling in 1928 changed how commercial buildings were cooled, but it was too expensive for the typical homeowner (4). After World War II, air-conditioning for comfort became increasingly popular prompting a change in the entire architecture of buildings. There was no longer a need to design buildings with comfort as a criteria because mechanical systems could make *any* building comfortable.

Today air-conditioning is a way of life in the United States. Almost 50% of all U.S. homes have air-conditioning, and 81% of all new homes constructed are equipped with central air-conditioning (5). Since 1940, eight of the 10 fastest growing cities in the United States are located in the hot southeast and southwest (4). This has been made possible with air-conditioning.

An entire industry exists to provide equipment to make people comfortable in buildings. The Air-Conditioning and Refrigeration Institute (ARI) reports that the value of shipments by heating, ventilation, and air conditioning (HVAC) manufacturers exceeded US$28 billion in 1996. With 52,000 chlorofluorocarbon (CFC) chillers yet to be replaced in the United States alone, there is a large market for new chillers, new technology, and new opportunities for the HVAC industry (5). In 1998 the United States manufactured 7,558 non-CFC chillers for use in the United States and abroad. The ARI indicates that new, non-CFC chillers will be 40% more efficient than CFC units installed 20 years ago. With less energy consumption comes lower CO_2 emissions from electrical generating plants.

The U.S. Environmental Protection Agency (EPA) predicts that 44% of the CFC chillers in existence during the early 1990s will be replaced or converted by the year 2000 (6). As a result, energy consumption will be reduced by 7 billion kilowatt hours/year from pre-replacement levels, resulting in a marked reduction in CO_2 production.

Sales in unitary equipment increased 16% in 1998 over the previous year. The trend indicates that the HVAC industry is responding to a robust market, that the market is significantly influenced by a concern for energy and the environment, and that advancements in technology are responding to those concerns.

So what can be surmised by this exponential growth in the use of air-conditioning? The trend indicates that demand for air-conditioning will continue to grow, as will the need for new technology. Other regions of the world will see similar growth, producing an increased impact on sustainability. As a result, the equipment will become more efficient and designers will create better systems in an effort to provide a sustainable future.

Contributions by technical societies.

Long before the term or concept of sustainability was in vogue, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE); the Chartered Institute of Building Service Engineers (CIBSE); and other technical societies were promoting the creation and use of environmentally conscious building technology. One of ASHRAE's most visible standards, ASHRAE Standard 90.1 "Energy Efficient Design of New Buildings Except Low-Rise Residential Buildings," was first adopted in 1975. Since then it has undergone numerous revisions.

Standard 90.1 is only one of a number of standards that ASHRAE produces that have a positive impact on the environment. A few examples include ASHRAE Standard 90.2, "Energy Code for New Low-Rise Residential Buildings," which is a companion document to 90.1. ASHRAE Standards 15 and 34 help accelerate the use of environmentally benign refrigerants. Standard 100 deals with energy conservation in existing buildings and Guideline 1 deals with building commissioning. Standard 109 concerns the rating of flat plate solar collectors.

Similarly, ASHRAE has actively supported research for decades. Today, 20% of its US$3,200,000 research budget is dedicated to energy conservation. Fifteen percent supports environmentally safe materials such as replacement refrigerants. Likewise, ASHRAE continues to offer educational programs related to sustainability such as its professional development seminar on "Building Retrofit for Energy

Efficiency." ASHRAE handbooks are one of many publications providing technical support for building designers, equipment manufacturers, contractors, and building operators.

Possibly the most succinct explanation of ASHRAE's commitment to sustainable buildings is found in its position statements and papers. For example, the ASHRAE's position on energy states, "ASHRAE will develop and distribute technical knowledge for design, application, installation and operation of energy efficient heating, ventilation, air conditioning and refrigeration with due regard for human health, comfort and environmental quality" (7). Similarly, the recently revised ASHRAE position on climate change states, "ASHRAE will continue to encourage the proper handling of all refrigerants to minimize losses to the atmosphere" (8).

Defining sustainability in buildings.

Sustainability has many definitions. Some point to the personal dimensions of sustainability, such as Robert Gilman's adaptation of the golden rule: "Sustainability refers to a very old and simple concept – the ability to keep going over the long haul. Think of it as extending the golden rule through time, so that you do unto future generations as you would have them do unto you" (9).

The Earth Summit in Rio concluded that sustainability means providing for the needs of the present without detracting from the ability to fulfil the needs of the future (10). These definitions and others focus on the fact that choices made today impact future generations. There is no doubt that the choices made in the design, construction, and operation of buildings impact the future and need much more than a cursory review based on first cost.

The creation of sustainable buildings is only a part of planetary sustainability. According to David McCloskey, Associate Professor of Sociology at Seattle University (11), actions are sustainable if:

- "There is a balance between resources used and resources regenerated.
- Resources are as clean (or cleaner) at end use as at the beginning.
- The viability, integrity, and diversity of natural systems are restored and maintained.
- They lead to enhanced local and regional self-reliance.
- They help create and maintain community and a culture of place.
- Each generation preserves the legacies of future generations."

Design based on the principles of sustainability is not a new approach. Many examples of sustainable design exist in the history of architecture, especially regionally appropriate vernacular dwellings. The best of ancient building approaches should be used in logical combination with the best new technological advances. Future buildings should be regarded as more than inanimate boxes. They should be complete systems capable of improving, recycling, and producing energy, clean water and air, building materials, food, beauty, and healthy human and biological communities. The building practices and design considerations identified by Public Technology Inc. and the U.S. Green Building Council (12) perhaps best express these goals:

- Seek to use resources only at the speed at which they naturally regenerate, and discard resources at which local ecosystems can absorb them;
- Material and energy resources are part of a balanced human/natural cycle. Waste occurs only to the extent that it is incorporated back into that cycle and used for the generation of more resources;
- Site planning that uses resources naturally available on the site, such as solar and wind energy, natural shading, and drainage;
- Use of resource efficient materials in construction of the building and in furnishings to lessen local and global impact;
- Minimization of energy and materials waste throughout the building's life cycle from design through reuse or demolition;
- Design of the building shell for energy efficiency;
- Use of material and design strategies to achieve total indoor environmental quality, of which indoor air quality is a major component;
- Design to maximize occupant health and productivity;
- Operation and maintenance systems that support waste reduction and recycling;
- Location and systems that optimize employee commuting and customer transportation options and minimize the use of single occupancy vehicles. These include using alternative work modes such as telecommuting and teleconferencing; and
- Management of water as a limited resource.

Design process.

A sustainable building is the result of an integrated design of interdependent, environmentally sound systems, components, and products. The potential of a sustainable building is best achieved by a team-oriented, multi-disciplinary approach in which all members of the project team recognize and commit to the steps and actions necessary to achieve the goals of the project. This presents a significant challenge for all involved, but is made easier when the client has the vision and desires to seek a sustainable solution. Typically, at the other end of the process, a contractor constructs the designed building. The early presence of a contractor can benefit the process through the knowledge of the assembly sequence and also by setting the stage for a more successful, environmentally sound construct.

It is essential that the design team agree on performance goals at the beginning of the design process. To meet these goals, the team must use building energy simulation tools to guide design decisions throughout the process. Table 1 summarizes an overall process for designing sustainable buildings, based on recommendations in the Bernheim and Reed's Sustainable Building Technical Manual (13), and a detailed process for completing the energy design, an important component of the overall process. The detailed energy design process given in Table 1 is based on the 9-step Energy Design Process that was discussed in the December 1999 *ASHRAE Journal* (14).

The two processes summarized in Table 1 demonstrate that there are multiple recommended methods for achieving low-energy goals. These methods have common themes – building envelopes and systems must compliment one another and it is essential that all pieces of a building design are thought of as a single system from the onset of the conceptual design through the completion of the commissioning process. The buildings described in the case studies summarized in the following section were designed and constructed in the early 1990s. At the time of their construction, cutting-edge energy features were incorporated for the same total construction cost as equivalent buildings where energy efficiency was not part of the design. Energy efficiency and renewable energy building features are becoming more common and less expensive to install, especially with the growing interest in sustainable building design. Although not all of the features incorporated in these buildings may be considered state-of-the-art in today's terms, the lessons learned from following the processes outlined in Table 1 and from practical experience gained from being a pioneer in implementing these sustainable features are still valuable today.

Table1. Processes for Designing and Constructing Sustainable Buildings

	BERNHEIM AND REED'S GREEN DESIGN PROCESS	9-STEP ENERGY DESIGN PROCESS
Pre-Design	• Develop green vision • Establish project goals and green design criteria • Set priorities • Develop building program • Establish budget • Assemble green team • Develop partnering strategies • Develop project schedule • Review laws and standards • Conduct research • Select site.	1) Create a base-case building model to quantify base-case energy use and costs. The base-case building is solar neutral (equal glazing areas on all wall orientations) and meets the requirements of applicable energy efficiency codes such as ASHRAE Standards 90.1 and 90.2. 2) Complete a parametric analysis to determine sensitivities to specific load components. Sequentially eliminate loads from the base-case building, such as conductive losses, lighting loads, solar gains, and plug loads. 3) Develop preliminary design solutions. The design team brainstorms possible solutions that may include strategies to reduce lighting and cooling loads by incorporating daylighting or to meet heating loads with passive solar heating.
Schematic Design	• Confirm green design criteria • Develop green solutions • Test green solutions • Select green solutions • Check cost.	4) Incorporate preliminary design solutions into a computer model of the proposed building design. Energy impact and cost effectiveness of each variant is determined by comparing the energy with the original base-case building and to the other variants. Those variants having the most favorable results should be incorporated into the building design. 5) Prepare preliminary set of construction drawings. These drawings are based on the decisions made in Step 4.

Design Development	• Refine green solutions • Develop test, select green systems • Check cost.	6) Identify an HVAC system that will meet the predicted loads. The HVAC system should work with the building envelope and exploit the specific climatic characteristics of the site for maximum efficiency. Often, the HVAC system is much smaller than in a typical building.
Construction Documents and Bid	• Document green materials and systems • Check cost. • Clarify green solutions • Establish cost • Sign contract.	7) Finalize plans and specifications. Ensure the building plans are properly detailed and that the specifications are accurate. The final design simulation should incorporate all cost-effective features. Savings exceeding 50% from a base-case building are frequently possible with this approach.
Construction	• Review substitutions and submittals for green products • Review materials test data • Build project • Commission the systems • Testing • Operations and maintenance manuals • Training.	8) Rerun simulations before design changes are made during construction. Verify that changes will not adversely affect the building's energy performance.
Occupancy	• Re-commission the systems • Perform maintenance • Conduct post-occupancy evaluation.	9) Commission all equipment and controls. Educate building operators. A building that is not properly commissioned will not meet the energy efficiency design goals. Building operators must understand how to properly operate the building to maximize its performance.

Case Study Examples of Sustainable Buildings

The following case studies describe two high-performance buildings: the Solar Energy Research Facility (SERF) and the Thermal Test Facility (TTF). Both buildings are located in Golden, Colorado U.S., and they both house laboratory and office spaces. Models calibrated with actual data show that the SERF and TTF incur 45% and 63% less energy cost, respectively, for heating, cooling, lighting, and hot water than equivalent buildings designed to comply with the U.S. Federal Energy Code 10CFR435 (based on ASHRAE Standard 90.1).

The Solar Energy Research Facility.

Completed in 1993, the 10,800 m^2 (115,200 ft^2) SERF houses highly specialized laboratory facilities along with typical commercial office building spaces (Figure 1). To meet the energy-efficiency goals, the design team carefully considered geometric organization and system zoning during the conceptual design phase. These issues must be considered in the earliest stages of conceptual design and are essential to creating a low-energy building. For the SERF, this planning ensured that the building's architecture improved the building's energy performance and responded appropriately to the south sloping site.

Figure 1. Solar Energy Research Facility

The laboratories required controlled lighting and high ventilation rates. Office space was needed to support laboratory activities. To meet these requirements, the building was aligned so that long sides of the building face north and south. The building was zoned so that the office pods were located in the front (south) portion of the building and the laboratories were placed in the north portion. As a result of this building configuration, daylighting and solar gains are used to light and supply solar heat to the offices. Also, the HVAC system could be split to meet the special environmental control needs of the laboratories separately from the rest of the building. Finally, by having a long north axis, high-quality diffuse daylighting through north-facing glazing is provided to the back of the building.

Daylighting plays an integral role in the design of the office pods. Stepped clerestory shelves (Figure 2) use the building's southern exposure to provide high-quality diffuse lighting for offices and adjoining corridors. Overhangs and side fins shade direct sunlight so that it would create uncomfortable glare and heat gains. Glazings with specific visual transmittance values were selected based on computer simulation results to control luminosity from the clerestory and east-west windows. The east-west glazing surfaces are further protected from glare and heat gain with a motorized window blind system activated by an exterior sun sensor. When the daylight is insufficient, high-efficiency T-8 fluorescent fixtures with electronic ballasts provide light. Motion detectors are used throughout the building to keep the lights off when spaces are not occupied. These systems reduce both lighting electricity use and cooling loads.

Figure 2. Stepped Clerestory Shelves for High-Quality Daylighting

The HVAC system was optimized based on the Colorado climate and the energy loads for the building. The system incorporates direct and indirect evaporative cooling, which is well suited for the dry Metro Denver-area climate. Direct evaporative systems use the heat of evaporation to lower air temperatures before distributing the air throughout the building. The indirect system uses the building cooling towers to produce chilled water through an intermediary heat exchanger. The chilled water is circulated through cooling coils to cool air streams without increasing humidity in the main air supply. The oversized cooling towers provide increased contact area between water to be cooled and the circulating air stream. The oversized cooling towers also reduce airflow pressure drop through the towers so less fan horsepower is required. This type of system is often called a "waterside economizer." The waterside economizer provides enough cooling capacity for the SERF so that the building chillers operate less than six months out of the year. Direct and indirect evaporative cooling systems use far less energy than conventional air-conditioning systems, and resulted in energy savings of about US$30,000 per year.

Building codes require 100% outside air for the laboratories. Heat exchangers preheat fresh incoming air with recovered heat generated by laboratory and HVAC equipment. The heat recovery system displaces 50% to 60% of the energy that would otherwise be required to heat incoming air. A solar thermal storage wall, known as a Trombe wall, was also incorporated into the building's shipping and receiving area to provide a radiant heat source in an area where the outside door is opened frequently. These heating strategies save about US$30,000 per year.

Variable frequency drives operate the ventilation system supply fans and the HVAC pumps. These drives operate at the speed needed to meet demand. The HVAC system also uses high-efficiency motors that require 2% to 3% less electricity than standard motors to produce the same mechanical output.

Table 2 shows the incremental first cost, energy cost savings, and simple paybacks for the energy reduction strategies used in the SERF. Table 3 summarizes the base-case building, predicted, and actual energy costs and savings for the SERF.

Table 2. Energy Costs, Savings, and Simple Payback for the SERF (US$)

STRATEGY	ADDED COST	ANNUAL SAVINGS	SIMPLE PAYBACK
Heat Recovery	$174,000	$28,000	6 years
Indirect/Direct Evaporative Cooling	$69,000	$30,000	2 years
Efficient Lighting	$54,000	$9,000	6 years
High-Efficiency Motors	$4,000	$2,000	2 years
Variable Frequency Drives	$6,000	$2,000	3 years
Upsize Cooling Towers	$6,000	$1,000	6 years
Daylighting/Zoning/ Geometry/Orientation	N/A	$110,000	N/A

Table 3. SERF Annual Energy Costs and Savings (US$)

END USE	CODE BUILDING (10CFR435)	SERF DESIGN PREDICTED	SERF ACTUAL CALIBRATED
Equipment/Plug Loads Energy Costs	$159,000	$159,000	$136,000
Lighting Energy Costs	$36,000	$14,000	$12,000
Cooling Energy Costs	$71,000	$11,000	$9,000
Heating Costs	$195,000	$111,000	$120,000
Domestic Hot Water Energy Costs	$1,000	$300	$300
HVAC Energy Costs	$102,000	$98,000	$83,000
Total Energy Costs (with equipment)	$565,000	$393,000	$360,000
Savings	N/A	$172,000 (30%)	$205,000 (36%)
Total Energy Costs (without equipment)	$406,000	$234,000	$224,000
Savings (without equipment)	$0,000	$172,000 (42%)	$182,000 (45%)
Building Size	10,800 m^2 (115,200 ft^2)	10,800 m^2 (115,200 ft^2)	10,800 m^2 (115,200 ft^2)

It is not possible to assign a precise incremental cost to the daylighting, zoning, geometry, and orientation modifications. All buildings have a certain "aesthetic cost," which is the cost associated with the architecture of the building. In this case, the aesthetic cost was applied in such a way as to also reduce the need for lighting, heating, and cooling energy. In other words, the architecture works with the building's energy needs.

Performance analysis. A post-construction analysis of the SERF's energy-saving features revealed additional savings opportunities with the lighting and HVAC systems. The office pods were designed with a security lighting system that remained on 24 hours a day (there were no controls beyond the electrical panel that allowed operators to turn off the security lights). In addition, the daylight and motion detectors throughout the building were not adjusted correctly, allowing some of the electric lights to remain on throughout the day. Maintaining proper calibration of light sensors is a common problem in lighting controls, and was even more prevalent in the generation of controls available when the SERF was constructed.

Simulations were completed to predict the energy savings from calibrating the SERF's daylighting and occupancy sensors using an hourly, building-energy simulation software tool. According to the simulations, calibration of the daylighting and occupancy sensors could provide an additional annual energy savings of US$1,800 and US$1,100, respectively. When the calibration was corrected, some occupants complained that the space seemed too dim. Light measurements in the space showed adequate ambient light levels. This discrepancy indicates that there is a psychological aspect to the lighting that may not be well understood.

The SERF daylighting system diffuses almost all the daylight by bouncing much of the light off the ceiling. An interior designer who had not been part of the design team specified the furniture and partition wall colors (shades of gray). These surface colors make the daylighting look "flat" and gray. Some occupants seem to be more satisfied when at least some ambient electric lighting is used to add a warmer color to the space, even though the electric lighting does not add appreciably to the measurable ambient light levels.

Most commercial buildings are internally load dominated such that cooling costs usually outweigh heating costs; however, in a carefully designed passive daylit building, waste heat from lights and unwanted solar gains are greatly reduced. In these buildings, the quality of the thermal envelope and the windows become very important to maintain comfort for occupants located at the perimeter. Factors related to comfort are not always apparent from the energy analysis and later surface after the building is occupied. Some occupants in the SERF experienced an uncomfortable chill on very cold days. It was necessary to install electric resistance heaters to maintain comfort on those cold days in some areas of the building. The values shown in Tables 2 and 3 include the electric resistant heater retrofit.

Table 4 shows the envelope and window thermal properties. These complied with code, and exceeded code for the low-e east and west windows. This experience demonstrates that payback analysis is not always appropriate when selecting energy features.

Table 4. SERF Envelope and Window Thermal Properties

ELEMENT	CONSTRUCTION	U-VALUE or R-VALUE	SOLAR HEAT GAIN COEFFICIENT (SHGC)
East and West Windows	Double-pane, 3/8", Low-e, aluminum frame	U-1.76 $W/m^2 \cdot K$ (U-0.31 $BTU/ft^2 \cdot hr \cdot °F$)	0.38
All others	Double-pane, 3/8" Aluminum frame	U-2.73 $W/m^2 \cdot K$ (U-0.48 $BTU/ft^2 \cdot hr \cdot °F$)	0.38
South Walls	Frame, fiberglass batt	R-3.80 $m^2 \cdot K/W$ (R-21.6 $ft^2 \cdot hr \cdot °F/BTU$)	N/A
East, West, North Walls	Concrete, fiberglass batt	R-3.96 $m^2 \cdot K/W$ (R-22.5 $ft^2 \cdot hr \cdot °F/BTU$)	N/A
Stepped Roof	Fiberglass batt	R-6.21 $m^2 \cdot K/W$ (R-35.3 $ft^2 \cdot hr \cdot °F/BTU$)	N/A
Flat Roof	Polyisocianurate, metal deck	R-3.65 $m^2 \cdot K/W$ (R-20.7 $ft^2 \cdot hr \cdot °F/BTU$)	N/A

Lessons learned. Overall, the SERF annual energy cost for heating, cooling, and lighting is approximately 45% less than an equivalent code-compliant building – remarkable for a laboratory building that houses very specialized functions. But as in all building projects, important lessons learned should be remembered when designing future building projects including:

- Diffuse ambient daylighting is required to avoid glare problems; however, there appears to be a psychological need for some warm light or varying light levels to create "sparkle." This sparkle can be met with small amounts of direct beam sun.
- The interior designer must be included in the design team and fully indoctrinated into daylighting design. This will ensure that interior surface colors for carpets, furniture, and partitions are appropriately specified and do not create dreary environments when only diffuse daylight is available.
- The thermal envelope and windows should be specified to ensure comfort at the perimeter, even though an energy analysis may not show cost justification to do this. These specifications include thermally-broken frames and low-e glass.

- Motion and photo-sensors are improving and becoming more cost effective, but there are still frequent calibration and control problems.
- The availability of new dimming technology should be used to compensate for variation in the daylighting.
- More guidance and tools are needed for building operators to optimize the control strategies in the building. Usage patterns in the building will change over time and the building controls should be adjusted accordingly.

The Thermal Test Facility.

When researchers began designing the TTF (Figure 3) in 1994, they took a strong approach to the whole-building design process. The first strategy researchers employed for the 929 m^2 (10,000 ft^2) facility was to establish a clear goal of 70% energy cost reduction from a code-compliant building at the onset of the conceptual design process. Designers then began optimizing the building design with detailed evaluations, using hourly simulation tools.

Figure 3. Thermal Test Facility

Like the SERF, the form of the building followed its functionality. To maximize the building's daylighting potential, the design team created a stepped building that accommodated clerestory windows for its mid- and high-bay laboratory areas. Daylighting meets all the TTF lighting needs except in the minimal-use areas of the building (restrooms, electrical rooms, etc.). Daylighting-occupancy sensors control operation of the electric lighting in the daylit areas, maintaining 540 lux (50-foot candles). Occupancy sensors govern electric lighting use in other areas. The daylighting-occupancy sensors for the electric lighting in the daylit spaces are on a single-step control system; the lights are either on or off. Controls have been optimized to prevent short cycling during periods of partial cloud cover.

High-efficiency T-8 bulbs with electronic ballasts and compact fluorescent fixtures meet electric lighting needs. Solid-state 2-watt exit signs also contribute to the building's reduced lighting energy requirements. The building contains no security lighting. The interior lights turn on when the occupancy sensors detect motion occurring within the building, eliminating the need for 24-hour security lighting. Data indicate that 2,630 kWh/year are saved by not operating 10% of the electric lighting 24 hours per day; the typical percentage of lighting dedicated to security lighting in commercial buildings.

Maximizing daylighting also led to the ability to passively heat and cool the building. Typical of commercial buildings that depend on daylighting to meet building lighting loads, the TTF has a higher than normal winter heating demand and potential overheating issues in the summer from too much solar gain. To address both these issues, overhangs for the clerestory windows were engineered to allow direct solar gain during the winter and eliminate solar gain during the summer. Heating loads in the low-bay portion of the building are less than in the remainder of the building because of internal gains in this office-use area. As a consequence, oversized overhangs were placed around the low-bay (office and conference room) windows to prevent direct solar gain almost year-round. These oversized overhangs minimize glare onto work surfaces and computer equipment in these office areas. Also, user-controlled aluminum venetian blinds can be adjusted to reflect sunlight to the ceiling.

The rear wall of the building is tilt-up concrete. The exterior side of the tilt-up concrete wall is covered with 5 cm (2 in.) of polystyrene insulation having an R-value of 1.8 $m^2 \cdot K/W$ (10 $hr \cdot ft^2 \cdot {}^oF/Btu$). The exterior stud walls are insulated with 3.75 cm (1.5 in.) of polystyrene insulation with an Exterior Insulated Finishing System (EIFS) finish and 15.24 cm (6 in.) of fiberglass batt insulation between the metal studs. The total R-value of the stud walls is 4.0 $m^2 \cdot K/W$ (23 $hr \cdot ft^2 \cdot {}^oF/Btu$).

The slab perimeter is insulated by a 1.2-m (4-ft) width of R-1.8 $m^2 \cdot K/W$ (R-10 $hr \cdot ft^2 \cdot {}^oF/Btu$) insulation. The roof is a metal decking over a steel structure. Ten centimeters (3 in.) of polyisocyanurate insulation on the roof yield a total R-value of 3.34 $m^2 \cdot K/W$ (19 $hr \cdot ft^2 \cdot {}^oF/Btu$). Designers were careful to eliminate thermal bridging between envelope components and the ground or outside environment. Thermally broken door and window frames were specified. The glazing for both view windows and clerestories is composed of insulating units having a U-value of 1.87 $W/m^2 \cdot K$ (0.33 $Btu/hr \cdot ft^2 \cdot {}^oF$) and a low-e coating. The clerestory windows have a high solar heat gain coefficient (SHGC of 0.68) for passive solar heating. The coefficient of the office and conference room windows is less (SHGC of 0.45) to help manage solar radiation and provide a gray tint for aesthetic purposes. Eighty-five percent of the glazing area faces south. Glass on the east and west faces was minimized because this glass cannot be effectively managed with overhangs and shading devices. North-facing glazing areas were sized to provide balanced daylighting. The energy saved by using daylighting (by not using the electric lights) outweighs the heat loss through the north-facing fenestration.

Thermostatically controlled ceiling fans distribute heated or cooled air throughout the building. Fan-powered, make-up air units with water heating coils operate if building heating loads cannot be met by passive solar heating. The main air handling units (AHUs) contain a hot-water heating coil and a direct/indirect evaporative cooler. A central heating plant in a neighboring building supplies hot water to the make-up air units and main AHU heating coils. When cooling is needed, the indirect section of the evaporative cooler operates first to avoid adding moisture to the building. A conventional economizer operates when outside conditions are right for supplying unconditioned air to the building. All duct runs in the building are as short and straight as possible to minimize static pressure losses through the ducts. Lower static pressure loss reduces energy consumption by the fans for air distribution, and air-to-air heat exchangers precondition ventilation air. These units operate during both the heating and cooling seasons, except when the economizer or evaporative cooler is operating.

One of the objectives of this design was to create a building that required minimal HVAC equipment and minimal run-times for the equipment. The building and the HVAC system were designed together as a single package to meet this objective. The building Energy Management System (EMS) optimizes the HVAC system operation. Table 5 outlines the operation sequence.

Table 5. Equipment Operation Sequence Based on Inside Temperature

COMPONENT	**LESS THAN 21.7°C (71°F)**	**21.7°C (71°F)**	**(22.2°C) (72°F)**	**22.8°C (73°F)**	**MORE THAN 22.8°C (73°F)**
Central Fan	Off	Off	Off	Economizer on	Evaporative cooler on
Evaporative Cooler (Direct)	Off	Off	Off	Off	On, if dew point < 18.3°C (65°F)
Evaporative Cooler (Indirect)	Off	Off	Off	Off	On
Make-up Air Unit Box Fans (w/ heating coil)	Modulates hot water valve to maintain zone temperature	Off	Off	Off	Off
Heat Exchange (HX)	Runs continuously except when the economizer or direct evaporative cooler are operating or when the building is unoccupied.				
Ceiling Fans	Operates on a 2.8°C- (5°F)-temperature difference from ceiling to floor to minimize stratification. Direction of fan blades determined by heating or cooling mode.				

Performance analysis. The HVAC system design and system operation in the TTF matches the load profile of the building. Figure 4, Chart A shows the distribution of energy costs for an equivalent code-compliant, base-case building developed by the simulation tools to compare the energy savings derived from implemented energy design strategies and technologies. Lighting watt densities are set at 15.1 W/m^2 (1.4 W/ft^2) in the code-compliant building. Figure 5, Chart B shows the predicted operating costs in the optimized building design, and Figure 5, Chart C shows the TTF's actual energy cost distribution. Annually, the TTF consumes only 234 million $J/m^2/yr$ (20,600 $Btu/ft^2/yr$) at a cost of US\$2.12/m^2 (US\$0.20/ft^2). Reasons for differences between operating and predicted costs are listed within the Lessons Learned section.

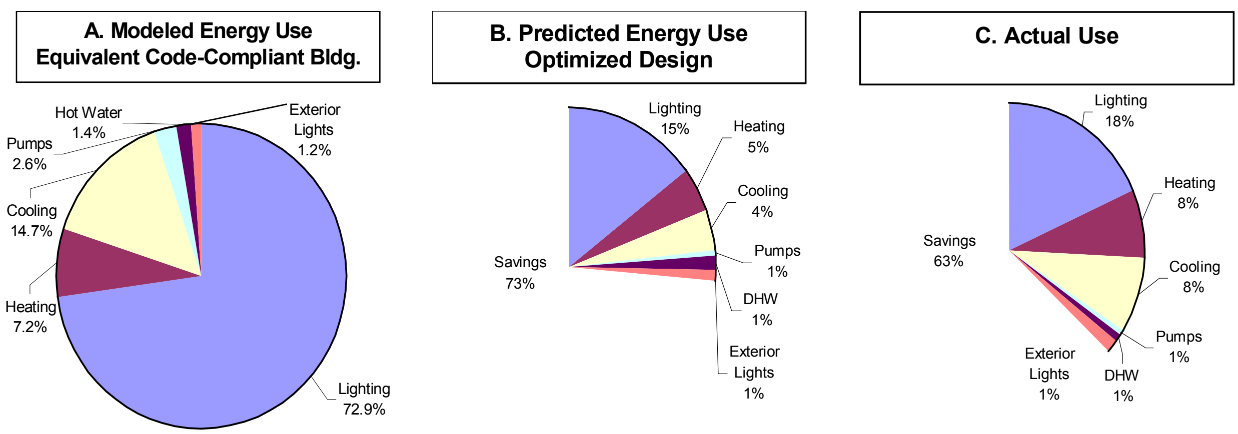

Figure 4. Energy use in the Thermal Test Facility

Lessons learned. The goal for the TTF energy cost performance was to be 70% less than an equivalent conventional building designed to meet the Federal Energy Code 10CFR435. After monitoring the building performance, researchers found the actual savings to be 63% compared to the code-compliant building.

The TTF's actual performance is less than was predicted, primarily for the following reasons:

- Through infrared imaging thermography, researchers discovered thermally-broken window and doorframes were not installed.
- A thermal bridge exists between the building foundation and an exterior retaining wall. A decision was made during construction to relocate the foundation insulation for structural reasons. By the time the researchers were made aware of the situation, the error could not be corrected without adding significantly to the project's cost.

Other lessons learned from monitoring the performance of the TTF are:

- Task lighting provide direct lighting to the work areas. Stepped controls cause some distraction. Using continuous dimming would further save energy while improving user satisfaction. When the building was designed, the high cost of continuous dimmable lighting controls prevented this level of lighting sophistication.
- Direct gain in the winter has caused some glare issues in the workplace. Light shelves and blinds can reduce this effect.
- The TTF has minimal airflow when heating and cooling are not required. Because of this, temperature stratification occurs, especially in the early morning hours. Ceiling fans need to be carefully placed to break up stratification without causing drafts.
- Temperature setback recovery times need to be carefully programmed because smaller equipment requires additional time to bring the building inside temperature to the desired level after a setback/setup period. Optimal start programs tend not to work well because they can not predict recovery times.
- Heat loss through the slab-on-grade floor is more than the simulation models predicted.
- Daylighting leads to lamp replacement cost savings. Lamps are rarely replaced because of the infrequent on-times.

Although an energy consultant-researcher was involved throughout the TTF's building process, window and slab insulation specifics were missed. Had these elements been included during construction, the original energy-conservation goal could have been met. This oversight shows the level of communication required between the energy consultant and other team members to ensure that all energy-saving features are incorporated and functioning properly from design through commissioning.

Renewable energy features.

Both the SERF and the TTF rely on solar technologies for lighting and heating. In addition, a 12-kW, grid-tied, photovoltaic (PV) system mounted on the roof of the SERF reduces the building's reliance on grid power. A PV system was also considered for the TTF. However, during the design process, it was determined that configuring the building architecture to optimize the daylighting design was a lower cost option for using the solar renewable resource compared to the cost of a PV system sized to meet an equivalent building lighting load. Finally, piping to accommodate a roof-mounted solar hot water system that will supply hot water for space heating was installed during the construction of the TTF. Research activities related to solar water heating systems is currently underway at the TTF, but these systems have not yet been connected to the building heating system.

Conclusions

The success of the TTF and SERF designs demonstrates that by closely following a whole building design process, a low-energy building can be constructed for nearly the same cost as a code-compliant building. Designers were required to stay within a prescribed budget for both buildings and both buildings were constructed for about the same price as typical laboratory buildings. Operating costs for the buildings are low. The TTF operating costs are US\$3.77/m^2 (US\$0.35/ft^2). When compared to conventional office building operating costs of US\$16.90/m^2 (US\$1.57/ft^2), the low operating costs of the TTF are remarkable (15). It should be noted that operating costs for conventional laboratory buildings are inherently larger than for office buildings because of the specialized research activities occurring within the building, making the comparison of the TTF's operating cost to an office building's operating cost even more impressive. The savings for the TTF translate directly into avoided emissions. For example, the electricity savings in the TTF avoid 79,600 lb. of CO_2, 460 lb. of SO_2, and 240 lb. of NO_x, annually.

Using the whole-building approach, members of the SERF and TTF design teams first established clear energy-performance goals and conducted detailed simulations. Team members then worked together using the modelling results as guides through the design, construction, and commissioning processes. Using a cooperative process, the design teams ensured that the building envelopes, internal systems, activities within the buildings, and the environment in which the buildings are located all work together as a single unit to operate more efficiently and energy. In addition, to the lessons learned that were summarized earlier in this paper, the design teams also concluded the following points.

- An energy consultant must be involved in the entire design process to help establish goals, brainstorm solutions, and provide simulation and analytical expertise.
- Two-stage evaporative coolers require different maintenance than traditional refrigerant-based systems.
- Daylighting can provide large savings. In addition, maintenance costs from bulb replacement is significantly reduced when fewer electric lights operate during daylighting periods. Control of light fixtures and glare must be considered as an integral part of the design.
- Each design stage must incorporate commitment to energy efficiency. Lack of a "watchful eye" can cause a decrease in savings.
- Low-energy buildings are similar in cost to traditionally built buildings when a whole building design approach is used.

Additional detailed technical information about the performance of the SERF and the TTF can be found in reports listed in the bibliography.

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In addition to impacting non-renewable energy supplies, buildings world wide contribute to climate change by being responsible for the release of carbon dioxide, either directly through combustion of carbon-based fuels or indirectly through electricity consumption from carbon fuels. As engineers and architects, we have an obligation to design for sustainability. This paper addresses each step in the building design process – from inception to occupancy. Recommendations and examples of how we can meet our obligations of sustainability are given using two examples of actual buildings that have low energy use and minimal impact on the environment. In addition, these buildings have life cycle costs comparable to conventional buildings and provide comfortable, healthy, and productive indoor environments.

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